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The 26 January 2001 *M* 7.6 Bhuj, India, Earthquake: Observed and Predicted Ground Motions

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Abstract Although local and regional instrumental recordings of the devastating 26, January 2001, Bhuj earthquake are sparse, the distribution of macroseismic effects can provide important constraints on the mainshock ground motions. We compiled available news accounts describing damage and other effects and interpreted them to obtain modified Mercalli intensities (MMIs) at >200 locations throughout the Indian subcontinent. These values are then used to map the intensity distribution throughout the subcontinent using a simple mathematical interpolation method. Although preliminary, the maps reveal several interesting features. Within the Kachchh region, the most heavily damaged villages are concentrated toward the western edge of the inferred fault, consistent with western directivity. Significant sediment-induced amplification is also suggested at a number of locations around the Gulf of Kachchh to the south of the epicenter. Away from the Kachchh region, intensities were clearly amplified significantly in areas that are along rivers, within deltas, or on coastal alluvium, such as mudflats and salt pans. In addition, we use fault-rupture parameters inferred from teleseismic data to predict shaking intensity at distances of 0–1000 km. We then convert the predicted hard-rock ground-motion parameters to MMI by using a relationship (derived from Internet-based intensity surveys) that assigns MMI based on the average effects in a region. The predicted MMIs are typically lower by 1–3 units than those estimated from news accounts, although they do predict near-field ground motions of approximately 80%*g* and potentially damaging ground motions on hard-rock sites to distances of approximately 300 km. For the most part, this discrepancy is consistent with the expected effect of sediment response, but it could also reflect other factors, such as unusually high building vulnerability in the Bhuj region and a tendency for media accounts to focus on the most dramatic damage, rather than the average effects. The discrepancy may also be partly attributable to the inadequacy of the empirical relationship between MMI and peak ground acceleration (PGA), when applied to India. The MMI–PGA relationship was developed using data from California earthquakes, which might have a systematically different stress drop and therefore, a different frequency content than intraplate events. When a relationship between response spectra and MMI is used, we obtain larger predicted MMI values, in better agreement with the observations.

Introduction

The *M* 7.6 Bhuj earthquake occurred in the state of Gujarat, India, at 03:16 UTC (8:16 a.m., local time) on 26 January 2001 (Fig. 1). The event struck within the Kachchh peninsula near India's western coast and was felt over much of the Indian subcontinent. Official government figures placed the death toll at over 20,000 and the number of injured at 166,000. Government estimates place direct economic losses due to the earthquake at 1.3 billion dollars, although more recent estimates indicate losses as high as 5 billion.

Eyewitnesses reported that approximately one building in 10 remained standing in Bhuj and Anjar, the closest large cities to the epicenter. Considerable damage was also reported in Hyderabad in southern Pakistan, whereas cities on the ancient Indian craton at similar distances from the epicenter were not severely shaken. Although some multistory concrete buildings completely collapsed in moderately shaken regions, many other structures remained intact, indicating that poor-quality construction aggravated the damage. This was evident to provincial administrators, because

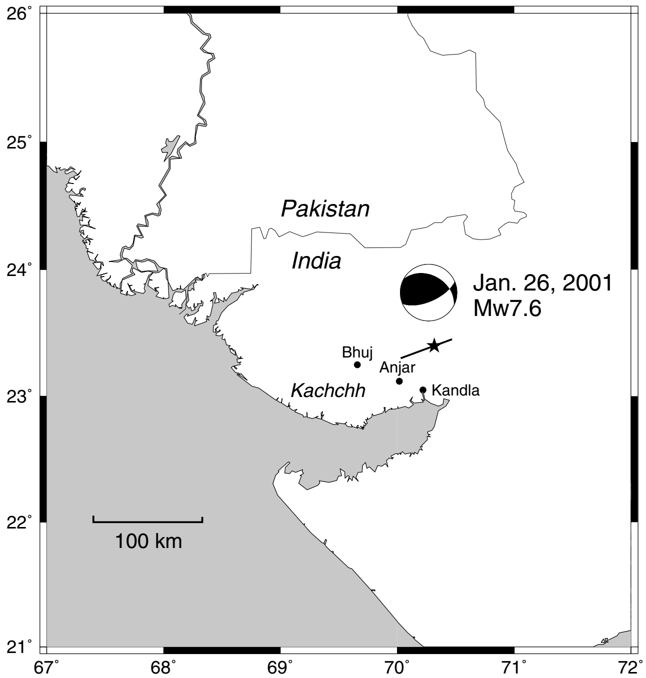


Figure 1. Map showing location of the 26 January 2001, Bhuj, India, earthquake within the Rann of Kachchh. The straight line shows a "pseudo-fault" with strike and length from Yagi and Kikuchi (2001). The focal mechanism corresponding to this solution is also shown. Preliminary aftershock relocations indicate a south-dipping rupture plane.

within a week of the event, Ahmedabad police had registered 37 cases of culpable homicide and criminal conspiracy against builders, architects, and engineers of buildings that collapsed in the earthquake.

The Bhuj earthquake generated substantial liquefaction and hydrological effects. Local hydrologists and villagers reported that the quake briefly activated desert rivers that had been dry for more than a century. Widespread liquefaction was confirmed by satellite imagery and by field observations (e.g., Tuttle *et al.*, 2001a, b). Many mud volcanos in the Rann of Kachchh have dimensions of tens of meters; one covered a 5-km-diameter stretch of the southern Rann with dark sand and mud. Numerous ancient river channels have been illuminated by a pock-mark pattern of vented sand and water, and some have clearly flowed and breached their old channels. Roads and fields near Bhachau were ruptured by 2–3-m-wide cracks resulting from substantial lateral spreading. The Port of Kandla was severely damaged by liquefaction and related ground failures, although numerous engineered structures, such as oil tanks, survived the earthquake.

The Bhuj earthquake occurred far from the edge of the Indian plate and quite close to an M 7.7 earthquake that occurred in 1819 (Oldham, 1926; Bilham, 1998). The 2001 felt region extends from Madras to Kathmandu, just as it did in the 1819 earthquake. Damage reports from Bhuj and Anjar are also strikingly similar to the damage reports of the 1819 earthquake. However, <2000 people were killed in the 1819 event. The population of Kachchh is now many times greater than in 1819, but the percentage of the local population killed is roughly the same, despite the implementation of a seismic-resistant building code.

Although instrumental recordings of the Bhuj earthquake are unfortunately scarce, isoseismal intensities provide an important data set. The distribution of strong-motion instruments in India is not adequate to calibrate directly the modified Mercalli intensity (MMI) values relative to physical ground-motion parameters. However, the Bhuj earthquake was well recorded at teleseismic distances. Intensity results from the Bhuj earthquake will thus be useful to better constrain the magnitude of historical Indian earthquakes (e.g., Ambraseys and Bilham, 2000).

Although a full compilation of shaking effects will not be available for some time, extensive news articles were written in the early aftermath of the Bhuj earthquake and were published in both conventional newspapers and on the Web. We compiled available accounts from reputable sources and interpreted them to obtain MMI values following conventional practice. The most difficult accounts to interpret are those that describe only liquefaction and/or disruption of underground water levels. Although recent evidence has shown that such effects can occur at relatively modest shaking levels (e.g., Musson, 1998), we have assigned MMI values according to the classic definitions in part to facilitate comparisons between our values and those determined for other earthquakes. Accordingly, such sites are given MMI values of VII–VIII, although we recognize the possibility that they may not reflect the overall level of ground motion. Our final data set includes MMI values for nearly 200 sites throughout the Indian subcontinent, with the highest concentration of values within 300 km of Bhuj.

We anticipate that our results will eventually be supplanted by MMI maps determined from ground observations and conventional mail surveys. However, we proceed with a determination of a "media-based intensity map" for two reasons. First, we believe the map does provide a good characterization of shaking effects throughout the subcontinent. More important, however, we construct our MMI map based solely on media accounts, so that the results can be compared with both media-based maps for earlier earthquakes and with the MMI distribution determined for the Bhuj earthquake from conventional ground- and mail-based surveys. These comparisons should provide useful insights into the nature of the biases that can result from determination of intensity distribution based only on news reports. Because such sources often provide the only source of information for older earthquakes (pre-1900, typically), the issue of "media biases" often looms large in the interpretation of intensity data for important historical earthquakes. Furthermore, it is likely that Web and media-based assessments will become increasingly common in future large earthquakes worldwide.

The Bhuj Mainshock: A Brief Overview

The preliminary focal mechanism of the Bhuj earthquake (e.g., Yagi and Kikuchi, 2001) suggests that the fault apparently occurred on a steeply dipping thrust fault that did not break the surface (Bendick *et al.*, 2001). The estimated moment magnitude, M_w, ranges from 7.5 to 7.7, suggesting a rupture of 15–30-km width, 50–100-km length, and average slip of 1–4 m. Preliminary results from aftershock studies indicate that the rupture was no shallower than about 8–9 km (Horton *et al.*, 2001). The surface manifestation of such a rupture is likely to be a broad zone of distributed uplift and subsidence with secondary surface faulting and cracking.

Parallels have been noted between the Bhuj earthquake and the 1811–1812 New Madrid sequence. It remains unclear, however, if the strain rates and/or overall tectonic settings of the two regions are analagous, but both the Bhuj earthquake and the largest New Madrid event (on 7 February 1812) occurred on thrust faults that failed to produce either extensive or pronounced surface ruptures (e.g., Mueller and Pujol, 2001). According to a recent reinterpretation by Hough *et al.* (2000), the magnitudes of these events may also have been similar. Results from studies of the Bhuj earthquake therefore have the potential to provide important insights for earthquakes in other areas.

Isoseismal Intensities

From methods such as ground-based and mail surveys, a full compilation of shaking effects from large earthquakes is typically not available for some time after the event. In the immediate aftermath of the Bhuj earthquake, we compiled news accounts from traditional print media sources in the United States and India as well as Internet-based sources. A summary of these reports, including their sources, is listed in Table 1. From the available accounts, we assigned MMIs (e.g., Stover and Coffman, 1993) based on the severity of shaking. In a few cases, news sources document that the event was not felt at a given location. In the Kachchh region, the most heavily damaged regions are generally assigned MMI values of IX–X, corresponding to heavy damage to masonry structures. Few values in excess of X are assigned, reflecting the paucity of accounts describing significant damage to modern, engineered structures. In the town of Sukhpur, however, one account describes a 10-year-old child being flung into the air. We assign an MMI of XI–XII for this location.

Intensity values can be interpreted as point data; our results for the Bhuj earthquake are shown in Figure 2. Typically, however, such data are used to define isoseismal contours. This approach is fraught with potential biases, as discussed at length by Hough *et al.* (2000). In particular, any general approach to interpolation or contouring will not reflect the systematic dependence of ground motions on site geology. Ideally, knowledge of local geological structure can provide important constraints, but such information is not readily available in this case.

To map the shaking distribution over the entire subcontinent, we use a simple mathematical approach, whereby the data are contoured using a continuous-curvature gridding algorithm. A uniform grid of estimated intensity values, $I(x,y)$, is determined by solving the equation

$$(1 - T) \cdot L[L(I)] + T \cdot L(I) = 0 \tag{1}$$

where T is a tension factor between 0 and 1, and L indicates the Laplacian operator (see Wessel and Smith, 1991). A tension factor of 0 yields the minimum-curvature solution, which can produce minima and maxima away from constrained values. With a value of 1, no minima or maxima occur away from control points. A tension factor of 1.0 is preferred because it avoids introduction of extreme values not constrained by data (Fig. 3). Figure 4 presents a close-up view of the Kachchh region.

The intensity maps reveal several interesting features. The event was felt only lightly at the higher-elevation cities on Deccan lavas throughout central and southern India. Away from the Kachchh region, intensities were clearly amplified significantly in areas that are along rivers, within deltas, or on coastal alluvium. One example is the Narmada River Valley in the province of Madhya Pradesh, where MMI values as high as VI were reached at distances of >600 km. Significant site effects were also observed within Mumbai (Bombay). Most of the city experienced shaking at the MMI V level, but intensities up to VI–VII were reached at areas built on landfill in southern and central Mumbai as well as along Bombay Harbor.

Interesting features can be seen in the intensity distribution within the Kachchh region as well. The most heavily damaged villages are concentrated toward the western edge of the inferred fault, suggesting substantial western directivity from the epicenter. Some of the largest mud volcanos were also documented in this region (Tuttle *et al.*, 2002). Significant sediment-induced amplification is also suggested at a number of locations around the Gulf of Kachchh, including towns immediately south of the epicenter and many of the villages on mudflats around the gulf.

The distribution of intensities in Kachchh are quite consistent with the spatial extent of liquefaction features as described by Tuttle *et al.* (2001, 2002). In northern Kachchh, the correspondence is not coincidental, as observations of liquefaction were used to assign some of the MMI values in some unpopulated areas. No liquefaction was observed in southwestern Kachchh, however, and the low MMI values in this region were assigned based on relatively light damage in this area.

Table 1
Bhuj Earthquake Intensities

Location	Lat.	Long.	MMI	Report	Source
Adhoi, Gujarat	23.400	70.513	9–10	Total devastation	*Kutchinfo.com*
Adipur, Gujarat	23.082	70.066	9–10	Total devastation	*Zee News*
Ahemadabad, Gujarat	23.043	72.578	7	Some damage	*The Indian Express*
Ahemadabad, Gujarat	23.030	72.577	7	Damage to mosque, bridge	(several)
Ahemadabad, Gujarat	23.009	72.590	7–8	Several high-rise buildings collapsed	(several)
Ahemadabad, Gujarat	23.009	72.568	7–8	Damage to soft-story high-rise buildings	*Outlook, Times of India*
Ahemadabad, Gujarat	23.050	72.577	6	Walls slightly cracked	*Zee News, Asian Age*
Ahemadabad, Gujarat	23.058	72.564	7–8	Water table rose 2.5 cm	*Times of India*
Ahemadabad, Gujarat	23.030	72.551	7–8	Several high-rise buildings collapsed	(several)
Ajmer, Rajasthan	26.270	74.420	6	Buildings cracked	*The Hindu*
Akola, Maharashtra	20.420	77.020	3	Felt lightly, duration estimated	*Sandhyanand*
Allahabad, Uttar Pradesh	25.280	81.540	3	Felt, many dizzy	*The Hindu*
Amravati, Maharashtra	20.560	77.480	3	Felt lightly, duration estimated	*Sandhyanand*
Amreli District, Gujarat	21.360	71.150	7–8	190 “Pucca” buildings destroyed	*Kutchinfo.com*
Anand District, Gujarat	22.320	73.000	6–7	Some buildings collapsed, many damaged	*Kutchinfo.com*
Anjar, Gujarat	23.117	70.019	10–11	Most old buildings leveled	*Asian Age, Zee News*
Ayyampettai, Tamil Nadu	10.902	79.182	3	Felt	*The Hindu*
Badin, Sindh (Pakistan)	24.663	68.838	8–9	Water emitted from cracks Building damage	*The Dawn*
Bagathala, Gujarat	22.847	70.717	8–9	Most buildings damaged or destroyed	*Asian Age*
Bahawalpur, Punjab (Pakistan)	29.391	71.699	6–7	Buildings cracked	*The Dawn*
Bajana, Gujarat	23.118	71.768	8	New springs	*Times of India*
Bakhasar, Rajasthan	24.430	71.090	7–8	Several buildings collapsed	*The Indian Express*
Balamba, Gujarat	22.716	70.436	8–9	Most buildings damaged or destroyed	*Zee News*
Bangalore, Karnataka	12.958	77.583	3–4	Felt widely, people ran outside	*The Hindu*
Bangladesh, Bangladesh	22.350	91.830	3	Felt, western and central regions	*123india.com*
Bapatla, Andhra Pradesh	15.905	80.466	3	Felt	*The Hindu*
Beraja, Gujarat	22.986	69.600	5–6	Cracks in buildings	*Panjokutch.com*
Bhachau, Gujarat	23.287	70.352	9–10	Most buildings destroyed	*Zee News* *Kutchinfo.com*
Bhadreshwar, Gujarat	22.916	69.891	8–9	Many buildings severely damaged	*Kutchinfo.com*
Bharuch, Gujarat	21.719	72.971	7–8	Several buildings damaged	*Kutchinfo.com*
Bhavnagar District, Gujarat	21.460	72.110	7	Many “pucca” buildings destroyed	*Kutchinfo.com*
Bhilwara, Rajasthan	25.210	74.400	6	Buildings cracked	*The Hindu*
Bhubaneshwar, Orissa	20.150	85.520	3	Felt	*Pragativadi*
Bhuj, Gujarat	23.245	69.662	11–12	Widespread devastation, pipes destroyed	(several)
Bhujpur, Gujarat	22.867	69.635	7–8	Ground level sunk (liquefaction)	*Panjokutch.com*
Bidada, Gujarat	22.900	69.463	6–7	Light damage	*Panjokutch.com*
Bidar, Karnataka	17.570	77.390	3	Felt	*Indiaexpress.com*
Buldhana, Maharashtra	20.320	76.140	3	Felt lightly, duration estimated	*Sandhyanand*
Butchireddipalem, Andhra Pradesh	14.531	79.884	3	Felt	*The Hindu*
Chandigarh, Chandigarh	30.420	76.540	3	Many people felt giddy/nauseous	ASC report
Chennai, Tamil Nadu	13.040	80.170	4	Kitchen utensils fell	*The Hindu*
Chhasra, Gujarat	22.969	69.816	8–9	80% Houses totally damaged	*Panjokutch.com*
Chidambaram, Andhra Pradesh	11.399	79.762	3	Felt	*The Hindu*
Chitrod, Gujarat	23.40	70.70	8	Damage to temple	INTACH field rep.
Cuddalore, Andhra Pradesh	11.753	79.769	3	Felt	*The Hindu*
Dalauda, Madhya Pradesh	23.934	75.099	NF	Not felt by observer ground	ASC report
Deesa, Gujarat	24.25	72.167	7–8	Church collapsed	*Indiaexpress.com*
Deshalpur, Gujarat	23.735	70.681	6–7	Light damage to village	*Panjokutch.com*
Dholavira, Gujarat	23.438	66.766	9	Archeological Society building destroyed	*Express*
Dhori, Gujarat	23.438	66.766	9–10	Fissures, sand blows, sand craters	Reuters, *Zee News*
Dhrandadhra, Gujarat	22.991	71.467	8	New springs	*Times of India*
Dhrol, Gujarat	22.574	70.407	8	Heavy damage	*www.xtechindia.com*
Dhule, Maharashtra	20.580	74.470	5	Felt strongly	*Kesri*
Dudhai, Gujarat	23.318	70.134	9–10	Most buildings destroyed	*Times of India*
Dwarka, Gujarat	22.247	68.965	8	Temples damaged	*Times of India*
Gandhidham, Gujarat	23.074	70.131	9–10	Many high-rise building collapsed	*Star News*, AP
Gandhinagar, Gujarat	23.296	72.635	8	Water table rose 2.5 cm	*Times of India*
Ganeshpuri-Vajreshwari Maharashtra	19.492	72.998	8	Change in hot springs temp., level	*Star News*
Ghotki, Sindh (Pakistan)	28.000	69.325	3	“Brief spell of earthquake”	*The Dawn*

(*continued*)

Table 1
Bhuj Earthquake Intensities (*continued*)

Location	Lat.	Long.	MMI	Report	Source
Goa (entire), Goa	14.200	74.000	3–4	People fled outside, articles rattled	*Sandhyanand*
Gundala, Gujarat	22.901	69.752	9–10	Heavy damage, all houses destroyed	*Kutchinfo.com*
Guntur, Andhra Pradesh	16.294	80.444	3	Felt	*The Hindu*
Gwalior, Madhya Pradesh	26.140	78.100	4–5	Felt strongly, utensils fell	*Sandhyanand*
Halvad, Gujarat	23.017	71.174	8	New springs	*Times of India*
Haryana (entire)	30.300	74.600	3	Felt for “around 20 sec.”	*Sandhyanand*
Himachal Pradesh	32.290	76.100	3	Felt for “around 20 sec.”	*Sandhyanand*
Hoshangabad, Madhya Pradesh	22.460	77.450	4–5	Felt strongly, utensils fell	*Sandhyanand*
Hyderabad, Sindh (Pakistan)	25.250	68.380	7–8	Damage to buildings, dozens injured	*The Dawn*
Hyderabad, Andhra Pradesh	17.387	78.480	2–3	Felt only in tall buildings	*The Hindu*
Jacobabad, Sindh (Pakistan)	28.279	68.428	3	“Brief spell of earthquake”	*The Dawn*
Jaipur, Rajasthan	26.893	75.790	6	Some buildings cracked	(check)
Jaiselmer, Rajasthan	26.914	70.790	7	Buildings cracked, damaged	*The Indian Express*
Jalgaon, Maharashtra	21.050	75.400	3	Felt	*Kesri*
Jalore, Rajasthan	25.220	72.580	6	Buildings cracked	*The Hindu*
Jamnagar, Gujarat	22.467	70.067	9	Many buildings destroyed	*Zee News* *Kutchinfo.com*
Jawaharnagar, Gujarat	23.367	69.986	10	Many buildings completely destroyed	*Indian Express*, AP
Jhinjhuwada, Gujarat	23.356	71.747	8	New springs	*Times of India*
Jodhpur, Rajasthan	21.883	70.033	7–8	Collapse of building dome	*The Indian Express*
Junagadh, Gujarat	21.516	70.457	7–8	Many buildings destroyed	*Kutchinfo.com*
Kabul (Afghanistan)	34.561	69.083	3	Felt	*The Indian Express*
Kandla, Gujarat	23.051	70.215	9	Many buildings severely damaged	(several)
Kandla Port Trust, Gujarat	22.982	70.218	9	Several buildings collapsed Piers damaged, widespread liquefaction	*Times of India*
Kanpur, Uttar Pradesh	26.280	80.240	3–4	Felt, furniture rattled	*Indiaexpress.com*
Karachi, Sindh (Pakistan)	24.510	67.040	5–6	Doors opened and closed, building cracks	ASC report
Kathmandu (Nepal)	27.734	85.282	3–4	Some reports of objects swinging	AFP
Kera Badadia, Gujarat	23.083	69.598	7	All buildings damaged	*Panjokutch.com*
Kerala	10.0	76.25	NF	Not felt	*Indiaexpress.com*
Khadan, Sindh (Pakistan)	24.492	68.987	9	6″ cracks, sand/water emitted	*The Dawn*
Khaipur, Sindh (Pakistan)	27.280	68.440	5–6	Some damage	*The Dawn*
Khangharpur, Gujarat	NL	NL	8–9	6″ cracks, sand/water emitted	Reuters
Kharaghodha Tank, Gujarat	23.231	71.747	8	New springs	*Times of India*
Khavda, Gujarat	23.840	69.720	9	Most buildings destroyed Possible mud volcano	*Times of India*
Kheda District, Gujarat	22.450	72.450	6–7	Many buildings damaged	*Kutchinfo.com*
Kolhapur, Maharashtra	16.707	79.224	3	Felt	*Indiaexpress.com*
Kolkata, West Bengal	22.340	88.240	3–4	Overhead fixtures swung	*Star News, Sandhyanand*
Kota, Rajasthan	25.178	75.835	6	Railway station cracked	*The Indian Express*
Kotdi-Roha, Gujarat	23.136	69.255	9	Two dead, heavy damage to KVO houses	*Panjokutch.com*
Kotri, Sindh (Pakistan)	25.220	68.220	4–5	25 women fainted, strong shaking	*The Dawn*
Koyna, Maharashtra	17.398	73.767	3–4	Felt for “around 40 sec.”	*Sandhyanand*
Kuda, Gujarat	23.113	71.385	8	New springs	*Times of India*
Kumbakakonam, Tamil Nadu	10.961	79.182	4–5	People ran, strongly felt	*The Hindu*
Lahore, Punjab (Pakistan)	31.542	74.399	4–5	Reported as “severe”	*The Dawn*
Larkana, Sindh (Pakistan)	27.330	68.150	3	“Brief spell of earthquake”	*The Dawn*
Lodhai, Gujarat	23.402	69.880	10–11	Most buildings distroyed	*Midday*
Lucknow, Uttar Pradesh	26.550	80.590	3–4	Furniture rattled	*Indiaexpress.com*
Luna, Gujarat	23.714	69.252	8–9	Water jet observed	*Kutchinfo.com*
Machilipatnam Andhra Pradesh	16.187	81.135	3	Felt	*The Hindu*
Maheshwari, Madhya Pradesh	22.110	75.370	6	Maheshwari fort cracked	*Sandhyanand*
Maliya, Gujarat	23.093	70.748	8	New springs, water levels increased	*Times of India*
Mandsaur, Madhya	23.030	75.080	5–6	Household articles knocked down	ASC report
Mandvi, Gujarat	22.834	69.343	9	Many buildings collapsed, bridges damaged	*Times of India*
Matiari, Sindh (Pakistan)	25.596	68.443	6–7	Wall collapse	*The Dawn*
Mehsana District, Gujarat	23.420	72.370	7–8	12 “pucca” buildings destroyed	*Kutchinfo.com*
Mirpurkhas, Sindh Pakistan	25.522	69.010	7–8	Walls and roofs collapsed	*The Dawn*
Mithi, Sindh (Pakistan)	24.732	69.792	7–8	Walls and roofs collapsed	*The Dawn*
Modhera, Gujarat	23.587	72.132	6–7	Sun Temple damaged	*Indya.com*
Morbi, Gujarat	22.811	70.827	8	Many buildings severely damaged	ASC report

(*continued*)

Table 1
Bhuj Earthquake Intensities (*continued*)

Location	Lat.	Long.	MMI	Report	Source
Mota Asambia, Gujarat	22.968	69.447	10	Most buildings destroyed	*Kutchinfo.com*
Multan, Punjab (Pakistan)	31.452	71.455	6–7	Buildings cracked	*The Dawn*
Mumbai (Andheri) Maharashtra	19.123	72.912	5	People fled outside	ASC report
Mumbai (Antop Hill) Maharashtra	19.028	72.843	6	Buildings cracked	*Sandhyanand*
Mumbai (Bandra) Maharashtra	19.058	72.836	3–4	Felt distinctly	ASC report
Mumbai (Colaba) Maharashtra	18.907	72.809	6	People fled into streets	*Sandhyanand*
Mumbai (Crawford Market) Maharashtra	18.950	72.829	6	Buildings cracked	ASC report
Mumbai (Dahisar) Maharashtra	19.258	72.837	5	Windows rattled	ASC report
Mumbai (Kurla) Maharashtra	19.076	72.912	6	Buildings cracked	*Kesri*
Mumbai (Malad) Maharashtra	19.183	72.832	4–5	Felt strongly	ASC report
Mumbai (Mankhurd) Maharashtra	19.050	72.931	6	Buildings cracked	*Sandhyanand*
Mumbai (Mazegaon) Maharashtra	18.968	72.841	6	Building cracked	ASC report
Mumbai (Mumbai Central) Maharashtra	18.993	72.827	6	Glassware broke, fixtures swung	ASC report
Mumbai (Navynagar) Maharashtra	18.912	72.813	5–6	People fled into streets	*Sandhyanand*
Mumbai (Vikhroli) Maharashtra	19.096	72.929	5–6	Building cracked	Sandhyanand
Mumbai (Wadala) Maharashtra	19.028	72.843	6–7	Section of fire station collapsed	*Sandhyanand*
Mumbai (Worli) Maharashtra	19.015	72.819	6	Felt strongly, building damage	*Times of India Sandhyanand*
Muzzafarnagar Uttar Pradesh	29.280	77.440	3	Felt by many	*Sandhyanand*
Nakhatrana, Gujarat	23.352	69.258	9	Sand blows, fountains	*Times of India*
Nalasopara, Maharashtra	19.417	72.782	5	Household objects shaken	ASC report
Nanded, Maharashtra	19.090	77.270	3	Felt lightly, duration estimated	*Sandhyanand*
Nandiad, Gujarat	22.687	72.854	7	Buildings visibly shaken	*BBC Talking Point*
Nandurbar, Maharashtra	21.230	74.190	3	Felt	*Kesri*
Nashik, Maharashtra	20.001	73.781	6–7	Several buildings damaged	*Sandhyanand*, ASC report
Naushahro Firoz, Sindh Pakistan	26.848	68.122	6–7	Buildings damaged	*The Dawn*
Navlakhi, Gujarat	22.969	70.464	8	Railway tracks submerged	*Asian Age*
				Liquefaction	*Times of India*
Navsari, Gujarat	20.954	72.919	7–8	98 “pucca” buildings collapsed	*Kutchinfo.com*
Nawabshah, Sindh Pakistan	26.236	68.394	7–8	Buildings damaged	*The Dawn*
New Delhi, NCT	28.380	77.120	3–4	Felt, overhead fixtures swung	*NDTV*
Neyvel, Andhra Pradesh	11.607	79.491	3	Felt	*The Hindu*
Nindo Shahr, Sindh	24.638	69.037	I	Several injured	*The Dawn*
Noida, Uttar Pradesh	28.605	77.260	3–4	Overhead fixtures swung	ASC report
Okha, Gujarat	22.462	69.061	8	Port facilities slightly damaged	*Sandhyanand*
Osmanabad, Maharashtra	18.080	76.060	3	Felt lightly, duration estimated	*Sandhyanand*
Palanpur, Gujarat	24.171	72.430	7–8	Many buildings collapsed	(several)
				Old bridge damaged	
Pali, Rajasthan	25.460	73.250	6	Buildings cracked	*The Hindu*
Papanad, Tamil Nadu	10.536	79.282	3	Felt	*The Hindu*
Papanasam, Tamil Nadu	10.922	79.270	3	Felt	*The Hindu*
Patan, Gujarat	23.874	72.109	7–8	Many buildings collapsed	*Kutchinfo.com*
Patdi, Gujarat	23.197	71.792	8	New springs	*The Times of India*
Patna, Bihar	25.370	85.130	3	Felt	*The Tribune*
Peshawar, NWFP Pakistan	33.276	71.860	3	Felt	*The Dawn*
Pokhran, Rajasthan	26.550	71.580	6	Buildings cracked	*Indian Express*
Pondicherry, (UT)	11.933	79.835	4–5	Celebrations disrupted, utensils fell	*The Hindu*
Ponnuru, Andhra Pradesh	16.067	80.560	3	Felt	*The Hindu*
Porbander, Gujarat	21.644	69.603	7–8	Many buildings destroyed	*Zee News, Kutchinfo.com*
Pune, Camp, Maharashtra	18.310	73.550	5	Furniture, windows rattled	ASC report
Pune, Hadapsar Maharashtra	18.503	73.887	NF	Observers were on ground floor	ASC report
Pune Lohegaon-Vimannagar Maharashtra	18.589	73.898	4–5	Windows and furniture rattled	ASC report
Pune, Lullanagar Maharashtra	18.496	73.859	3	Felt	ASC report
Pune, Sassoon Road Maharashtra	18.533	73.853	4–5	Household articles, furniture shook	ASC report
Punjab (entire)	30.400	75.500	3	Felt for “around 20 sec.”	*Sandhyanand*
Quetta, Baluchistan (Pakistan)	30.309	67.019	3	Felt	*The Dawn*
Radhanpur, Gujarat	23.841	71.603	6	Concrete water tanks swayed	USGS report
Rajkot, Gujarat	22.301	70.801	7–8	Many buildings collapsed	*Zee News Times of India*
Rapar, Gujarat	23.576	70.641	10	Most buildings destroyed	(several)
Ratnal, Gujarat	23.194	69.870	10	Most buildings destroyed	*Kutchinfo.com*
Rohri, Sindh (Pakistan)	27.410	68.570	3	“Brief spell of earthquake”	*The Dawn*
Salem, Tamil Nadu	11.390	78.120	NF	Not felt	ASC report

(*continued*)

Table 1
Bhuj Earthquake Intensities (*continued*)

Location	Lat.	Long.	MMI	Report	Source
Samakhiali, Gujarat	23.329	70.587	9	Water flooded salt pans ground cracking	*Times of India*
Sanghar, Sindh (Pakistan)	26.050	68.937	6–7	Buildings damaged	*The Dawn*
Shikarpur, Sindh (Pakistan)	27.965	68.635	3	"Brief spell of earthquake"	*The Dawn*
Shillong, Meghalaya	25.340	91.560	3	Felt	*Sandhyanand*
Sirohi, Rajasthan	24.530	72.540	6	Buildings cracked	*The Hindu*
Sukhpur, Gujarat	23.232	69.600	11–12	10-yr old "flung into air"	*The Asian Age*
Sukkur, Sindh (Pakistan)	27.693	68.845	3	"Brief spell of earthquake"	*The Dawn*
Suraj Bari, Gujarat	23.207	70.703	8–9	Serious cracks in land bridge	*Times of India*
Surat, Gujarat	21.193	72.822	7–8	A few high-rise buildings collapsed Nuclear reactor fba not triggered, Indicating shaking less than 0.1g	(several)
Surendranagar, Gujarat	22.706	71.678	8	Many old buildings destroyed	*Star News*
Suvi, Gujarat	23.618	70.483	9–10	Damage to dam	IIT Kanpur
Tada, Andhra Pradesh	13.586	80.030	3	Felt	*The Hindu*
Tadepalli, Andhra Pradesh	16.477	80.601	3	Felt	*The Hindu*
Talhar, Sindh (Pakistan)	24.894	68.806	I	Two injured	*The Dawn*
Tando Allah Yar, Sindh (Pakistan)	25.459	68.716	6–7	Wall collapse, 1 dead	*The Dawn*
Tarapur, Maharashtra	19.880	73.688	5–6	Reactors did not shut down	ASC report
Thane, Maharashtra	19.120	73.020	4	Felt strongly, esp. on upper floors	ASC report
Thatta, Sindh (Pakistan)	24.751	67.923	6–7	3 motorbike riders lost control	*The Dawn*
Thiruvaiyaru, Tamil Nadu	10.884	79.098	4–5	Some objects fell in market	*The Hindu*
Tivim, Goa	15.598	73.831	NF	Not felt	ASC report
Tonk District Rajasthan	26.110	75.500	6	Buildings cracked	*The Hindu*
Udaipur, Rajasthan	27.420	75.330	7	Serious damage to factory	*Sandhyanand*
Ujjain, Madhya Pradesh	23.090	77.430	4–5	Felt strongly, utensils fell	*Sandhyanand*
Unchahar, Uttar Pradesh	25.857	81.630	3	Many people felt giddy/naseuos	ASC report
Unnao, Uttar Pradesh	26.480	80.430	3–4	Furniture shook	*Indiaexpress.com*
Vadala, Gujarat	22.918	69.850	7–8	Most houses damaged, few collapsed	*Panjokutch.com*
Vadodara, Gujarat	22.303	73.187	6	Minor damage to buildings	ASC report
Valsad, Gujarat	20.611	72.924	7	Many buildings damaged	*Kutchinfo.com*
Vidisha, Madhya Pradesh	23.320	77.510	4–5	Felt strongly, utensils fell	*Sandhyanand*
Vijayawada, Andhra Pradesh	16.517	80.635	3	Felt	ASC report
Vishakhapatnam, Andhra Pradesh	17.728	83.304	3	Felt	*The Hindu*
Vondh, Gujarat	23.301	70.397	10	Most old buildings collapsed Some newer structures badly damaged	*Zee News*, AP
Wankaner, Gujarat	22.612	70.934	7	Fallen masonry	*Times of India*

Location: city, province, and country (if not India).

Predicted Ground Motions

Although the Bhuj earthquake was not recorded by strong-motion instruments, it was well recorded at teleseismic distances (e.g., Yagi and Kikuchi, 2001). We use a simplified source model determined from instrumental data to predict ground motions at local and regional distances using the finite-fault method of Beresnev and Atkinson (1997). This analysis is complicated by the fact that neither the ground motions nor the fault parameters are well constrained. We therefore seek to investigate only the general consistency between the inferred and predicted ground motions.

Our fault model is based on the moment, strike, dip, and rake determined by the U.S. Geological Survey, assuming a south-dipping fault plane (see Fig. 1). We use a moment magnitude of 7.6, consistent with finite-fault inversions from teleseismic data (Yagi and Kikuchi, 2001). We assume a rupture length of 50 km based on preliminary aftershock results (e.g., Horton *et al.*, 2001) and use an initial fault depth of 9 km based on preliminary analysis of geodetic data. Finally, we use a smooth-rupture model in which the average slip is determined from the moment and fault area. We calculate ground motions for hard-rock-site conditions ($\kappa = 0.005$; shear-wave velocity $= 3.7$ km/sec) and consider the issue of site response only in a qualitative manner. No crustal amplification is applied to the predictions. For our attenuation model, we use the results of Singh *et al.* (1999) for *Lg* attenuation in India: $Q = 508f^{0.48}$. We use a geometrical spreading function that includes an r^{-1} decay from 0 to 50 km and an $r^{-0.5}$ decay beyond 50 km, a slightly simpler form of the function assumed by Singh *et al.* (1999).

In the Beresnev and Atkinson (1997) approach, a rupture is simulated using fault-plane subelements, each of which is treated as a point source with a spectral shape constrained to have an ω^2 shape. The method is attractive for this application because of its computational ease and because there are few model parameters to be assigned. It is

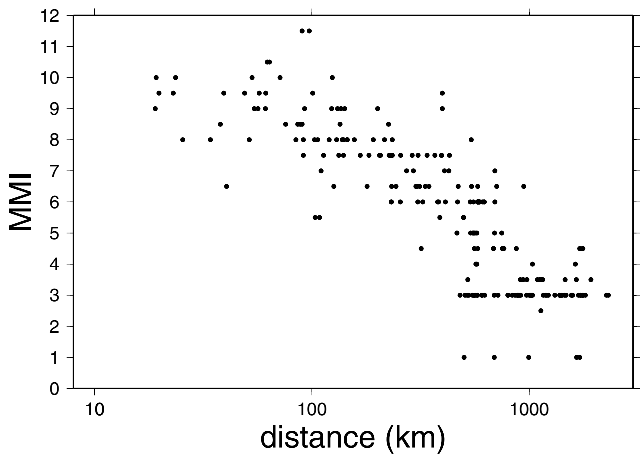


Figure 2. Inferred MMI values for the Bhuj earthquake are shown as a function of distance from the source. To estimate source distance, we calculate the nearest distance from each point to the "pseudo-fault" shown in Figure 1.

limited in its ability to model the time-domain characteristics of low-frequency ground motions, but we consider it likely that the damage from the Bhuj earthquake is primarily controlled by relatively high-frequency shaking.

The most important free parameter in this method is the "strength parameter," S_f, which is related to the maximum slip velocity, v_m, according to

$$v_m = 0.618y(\Delta\sigma)S_f/(\rho\beta) \tag{2}$$

where β is the shear-wave velocity, y is the rupture-propagation velocity as a fraction of β, $\Delta\sigma$ is the subevent stress drop, and ρ is density (Beresnev and Atkinson, 2001). Although rupture velocity can vary along strike, the formulation of Beresnev and Atkinson (2002) includes only a single value of S_f for each rupture model. As discussed by Beresnev and Atkinson (2001), the amplitude of high-frequency radiation depends strongly on S_f. S_f was found to vary between 1.0 and 2.4 for a wide range of earthquakes in eastern and western North America. In our application, the depth of faulting is another unknown. We therefore calculate peak ground acceleration (PGA) for a suite of possible rupture models with varying depths and strength parameters. We vary the depth to the upper edge of the rupture between 3 and 9 km and vary the strength factor between 1.4 and 2.0.

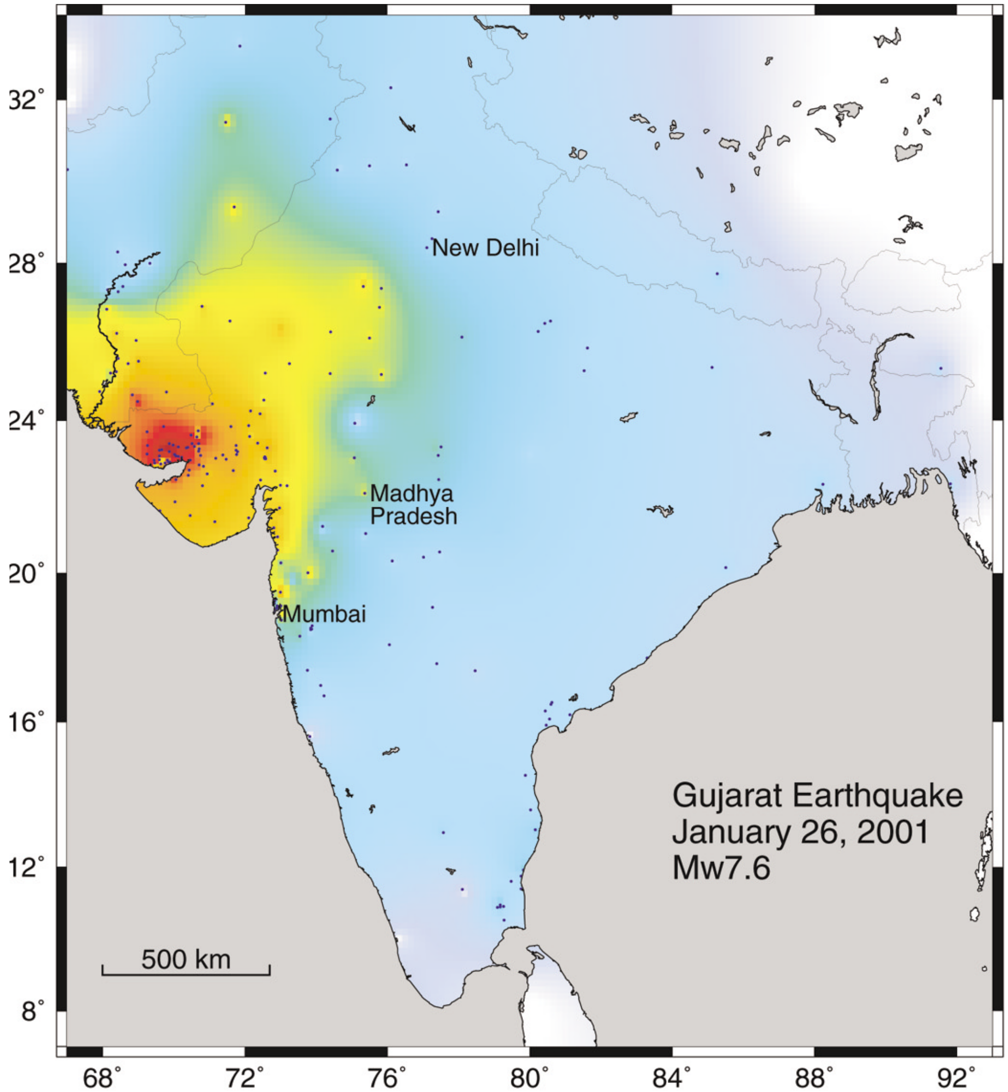
Figure 5a, b shows the predicted ground motions for hard-rock-site conditions as a function of distance for models in which strength factor and depth are varied, respectively. We conclude that predicted ground motions are more sensitive to the strength factor than to depth. Unfortunately, it is difficult to constrain the strength parameter (or, equivalently, the slip velocity.) For North America, its average value is 1.6 (Beresnev and Atkinson, 2002). We find that a strength factor close to this value (1.8) predicts a PGA of 10%g at the distance of Ahmedabad, consistent with the single strong-motion recording that was released in the aftermath of the earthquake (Fig. 5a). According to available reports, this instrument was located on a hard-rock site. There is some question, however, whether or not this instrument functioned properly (S. K. Singh, personal comm., 2002).

S. K. Singh *et al.* (unpublished manuscript) present the broadband data recorded from the Bhuj earthquake at distances of 565 to well $>$1000 km. Their peak acceleration values are also shown on Figure 5a for stations within 1350 km. These more-distant recordings appear to be consistent with a somewhat lower value of S_f, although at large distances, the ground-motion curves are increasingly controlled by attenuation rather than S_f. We therefore adopt a preferred value of 1.6. With the other assumed fault parameters, this predicts near-field hard-rock ground motions of approximately 80%g. The value of S_f is clearly quite uncertain, however, with other plausible values implying near-field ground motions approximately 20% higher and lower.

To compare predicted and estimated intensities, we convert predicted PGA to MMI by using the calibration established by Wald *et al.* (1999). It should be borne in mind that PGA (and thus, MMI) is predicted for rock sites and that MMI on soil will be as much as 1–2 units larger than on rock (Hough *et al.*, 2000; Atkinson, 2001). Although it is clearly difficult to compare data and models in cases where both are uncertain, we find that the predicted ground motions are able to match several salient features of the shaking distribution determined from MMI data. In both data and models, we find the highest shaking to the north and northwest of the epicenter and relatively low shaking to the southwest of the epicenter, as shown in Figure 6a.

For a wide range of strength factors, the model corroborates the macroseismic observation that potentially damaging ground motions can occur at distances of at least several hundred kilometers from the source. That is, PGAs on the order of 5%g generally correspond with the threshold of damage (e.g., Wald *et al.*, 1999). Values near or above this value are predicted (for our preferred model) to a distance of nearly 400 km. Moreover, because site response at soil sites can typically elevate MMI values by 1–2 units (e.g., Hough *et al.*, 2000; Atkinson, 2001), the predicted hard-rock ground motions (Fig. 6a) are high enough to cause damage at soft-sediment sites especially, over the extent of the MMI IV region in these figures. (Values near or above 2.5%g are predicted for distances upward of 500 km in our preferred model.)

The residuals between observed intensities and those predicted on rock shown in Figure 7 are also interesting to consider. These are calculated simply by subtracting the predicted MMI values from those observed. We calculate residuals by using ground-motion predictions determined for S_f = 1.6 and find that most values are between 1 and 3 MMI units. The distribution of residuals is generally consistent with expectations for site response, as especially high residuals are found at presumed sediment sites to the northeast and southeast of the rupture. Relatively low residuals are

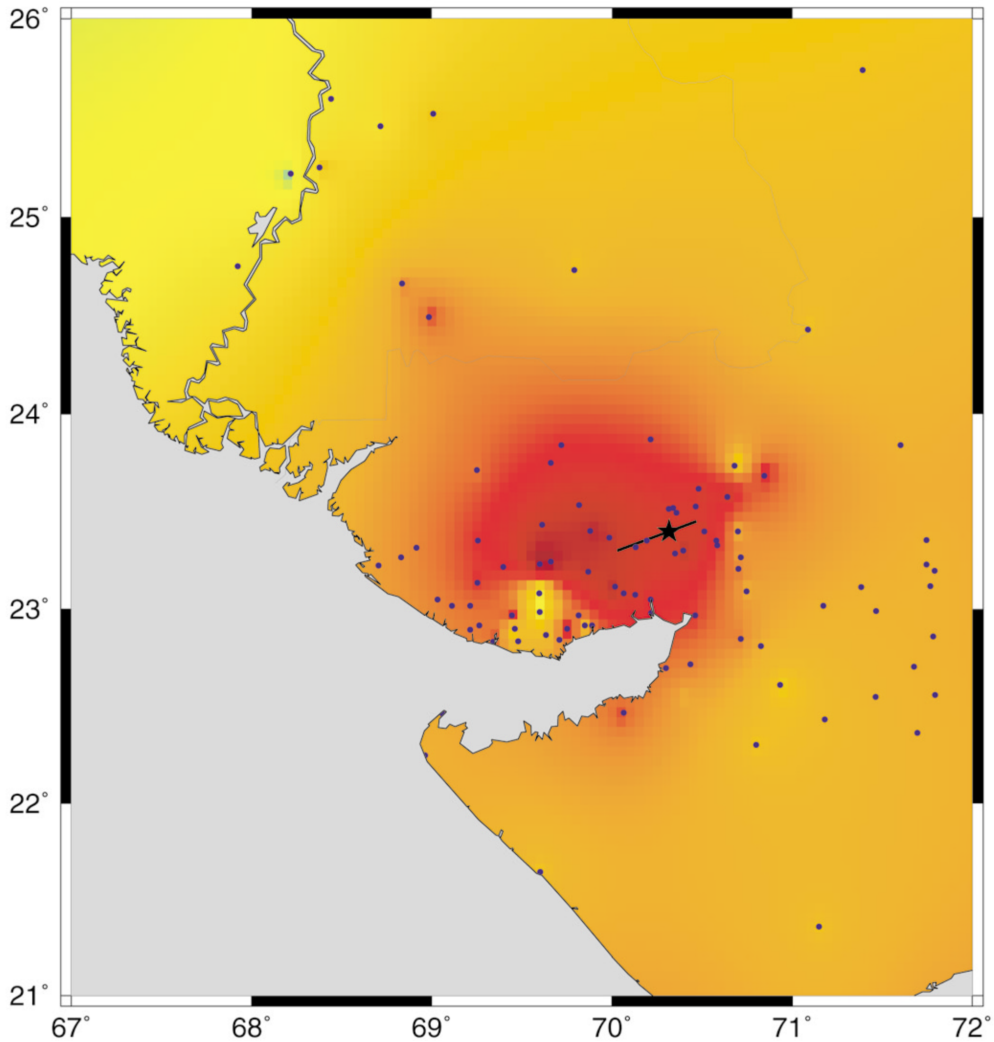


PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	***<.17***	***.17-1.4***	***1.4-3.9***	***3.9-9.2***	***9.2-18***	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	***16-31***	***31-60***	***60-116***	***>116***
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 3. Map of intensity distribution for the 2001 Bhuj earthquake determined using a smoothing parameter of 1.0. MMI values are constrained at approximately 200 locations indicated with small circles. Colors reflect MMI values according to scale shown at bottom of figure. Ground-motion parameters corresponding to each MMI value are from recent earthquakes in California (Wald *et al.*, 1999).

also found at locations to the southeast, which lie on Deccan lavas.

A coherent band of low residuals is also observed along the Indus River in Pakistan. Regional geological maps indicate that these sites should be alluvial. However, we speculate that the relatively low ground motions in this region may reflect path rather than site effects. That is, the active plate boundary west and northwest of Gujarat will likely disrupt coherent *Lg* wave propagation, which will give rise to a higher apparent attenuation and lower intensities (Kennett, 1989; Hanks and Johnston, 1992). Considering the spatial distribution of residuals, we speculate that the true regional attenuation curve might be somewhat steeper than that predicted by Singh *et al.* (1999).



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	*16-31*	*31-60*	*60-116*	*>116*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 4. Close-up view of intensity distribution in the Kachchh region (see caption for Fig. 3).

Within 100 km of the fault, however, ground motions estimated from our MMI values are systematically higher than those predicted by the model, typically by 1–3 units. It is possible that most of this discrepancy is due to site response, which will tend to increase MMI on soil sites by at least 1 unit relative to that on rock sites. Other factors that may also be important are (1) the vulnerability of local buildings to shaking (2) a tendency for media accounts to focus on the most extreme damage in hard-hit regions, especially in large cities, and (3) the nature of the ground motions in an intraplate region. It is difficult to estimate the bias contributed by each effect. However, we consider it unlikely that moderate estimated MMI values (IV–VI) are significantly amplified because of building vulnerability, because these values reflect light damage (cracking of walls) and other effects (objects being knocked off shelves) that should not depend strongly on building type. It therefore appears likely that the other two factors account for more of the unit discrepancy, at least at close distances. Because news accounts generally focus on the most extreme rather than the typical damage in a region, it is not surprising that MMI values derived from media accounts will be systematically

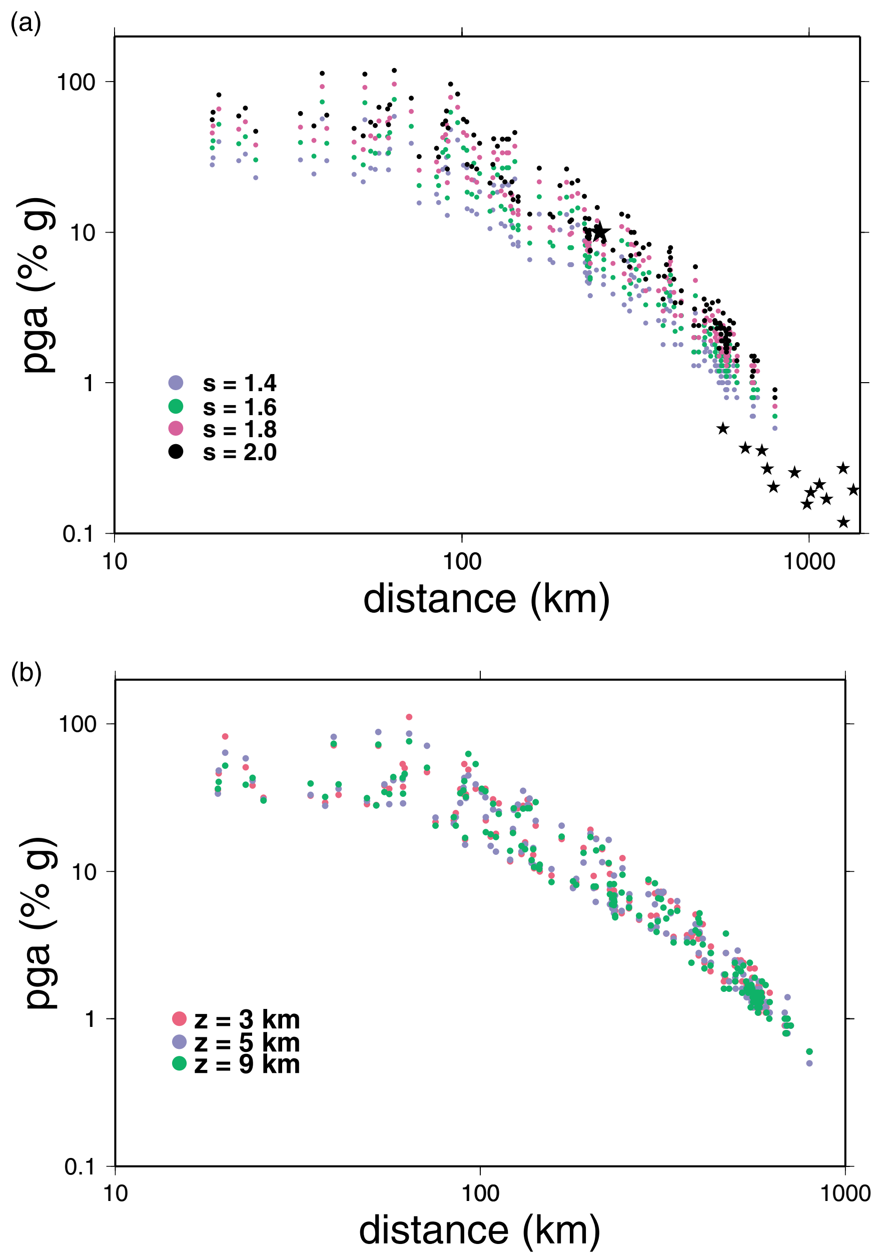
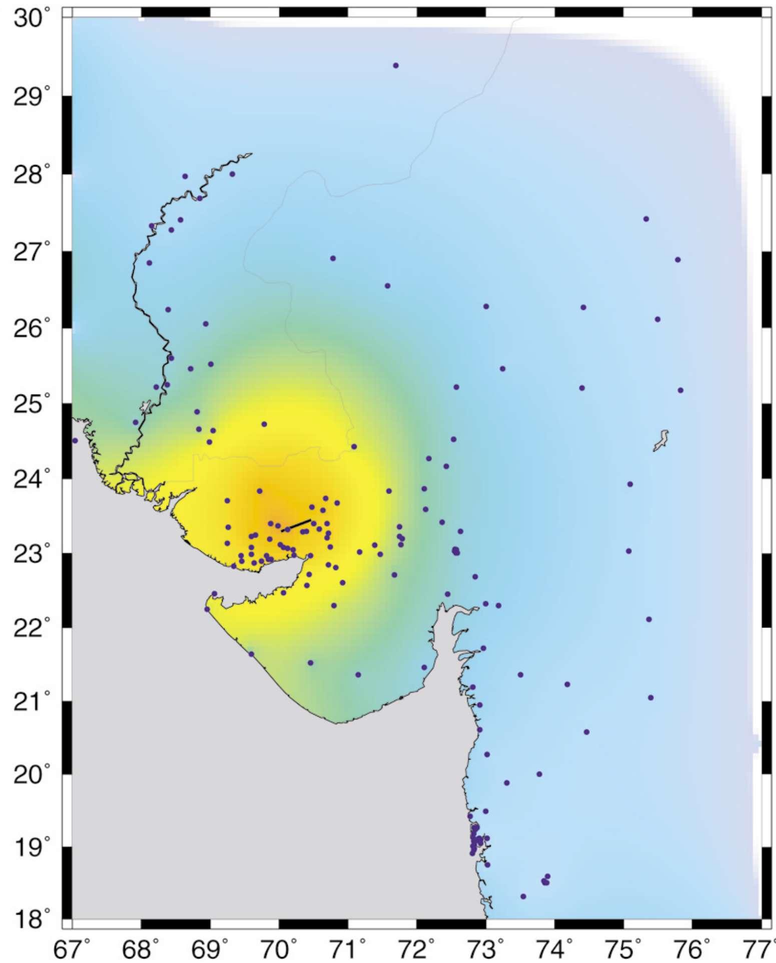


Figure 5. (a) PGA values predicted on rock by the finite-fault model of Beresnev and Atkinson (1997) for strength factors that vary between 1.4 and 2.0. (b) PGA values predicted on rock by the finite-fault model of Beresnev and Atkinson (1997) for models in which the rupture terminates at 3-, 5-, and 9-km depth.

higher than those determined from average effects, in the manner employed by the Wald *et al.* (1999) study. Even at low shaking levels, a media account might describe only the relately dramatic effects that occurred in a given location.

One must also consider the possibility that a PGA–MMI relationship determined for earthquakes in California is not appropriate for an intraplate region. In particular, it has been suggested that, by virtue of having a higher average stress drop, intraplate ground motions might be characterized by a higher level of high-frequency energy and therefore be more damaging (to some types of structures especially) than those from comparable earthquakes in interplate regions (e.g., Greig and Atkinson, 1993; Atkinson, 2001). To test this possibility, we recalculate predicted MMI values for a small number of locations by using relationships between MMI and response spectra determined by Atkinson and Sonley (2000). These relationships are also determined for earthquakes in California. However, Atkinson (2001) validates their applicability in intraplate regions by using the 1988 Saguenay earthquake and argues that the relationships are generally appropriate because frequency content is handled explicitly. Figure 8 presents the MMI results determined from both PGA

(a)



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	*16-31*	*31-60*	*60-116*	*>116*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

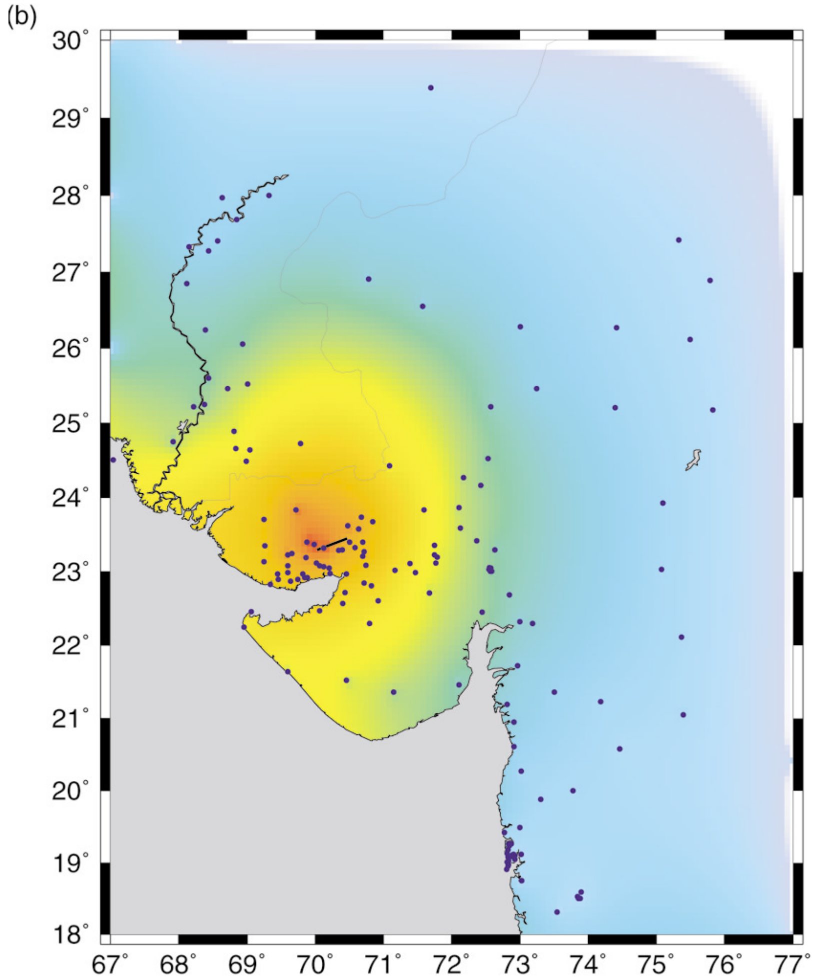
Figure 6. Predicted ground motions on rock for models with strength factors of 1.6 (a) and 2.0 (b). Note that intensities on soil would be 1–2 units higher. (*continued*)

and response spectra, both on rock, and shows that the latter are indeed higher than the former. On average, the MMI values are increased by approximately 1 unit when the response spectra relations are used. If one considers the expected influence of site response, the MMIs predicted from response spectra are in reasonably good agreement with the observations.

Implications for the 1811–1812 New Madrid Earthquakes

The parallels between the Bhuj earthquake and the 1811–1812 New Madrid earthquakes are so striking as to have been commented on within days (or even hours) of the event. However, the extent to which the earthquakes and source regions are analagous has been the subject of some debate, as Gujarat is much closer to a plate boundary than is New Madrid. Both source regions appear to be failed rift systems that generate their largest earthquakes on thrust faults favorably oriented for slip in the current stress regime (e.g., Bendick *et al.*, 2001). Also, both the Bhuj earthquake and the 7 February 1812, New Madrid earthquake appear to have been of similar size (Hough *et al.*, 2000), with neither event generating an extensive surface rupture.

In its shaking effects, the Bhuj earthquake appears to have been very similar to the largest New Madrid event,



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
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INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 6. (*Continued*).

which, according to the interpretation of Hough *et al.* (2000), occurred on 7 February 1812. Hough *et al.* (2000) inferred an *M* of 7.4–7.5 for this event; previous studies had inferred *M* values as high as 8.0 (Johnston, 1996a, b).

The shaking effects of the Bhuj and the three principal 1811–1812 New Madrid mainshocks were very similar. All of these events were felt at coastal regions as far as 2000 km from the epicenter, all caused light damage at sediment sites as far as 600 km away, and all generated substantial liquefaction over an atypically large region. After the Bhuj earthquake, liquefaction was reported as far as 250 km from the fault, similar to the extent of liquefaction generated by the 1811–1812 New Madrid sequence (Tuttle *et al.*, 2001a).

To compare the shaking effects of the Bhuj and New Madrid earthquakes, we present a comparison of MMI data as a function of distance from this study and from Hough *et al.* (2000). Figure 9 presents the results for both the 16 December 1811 and the 7 February 1812, New Madrid events.

The comparisons illustrated in Figure 9 are complicated by the fact that the December and February New Madrid mainshocks occurred at approximately 2:15 a.m. and 3:45 a.m. (local time), whereas the Bhuj earthquake occurred later in the morning. Hough *et al.* (2000) assigned MMI values of IV for all locations at which these New Madrid events were reported as "felt," because intensity IV is the level of shaking at which a few people will be wakened. Hough *et al.* (2000) additionally find that the December event was not felt at approximately 15 locations at distances of 800–1900 km.

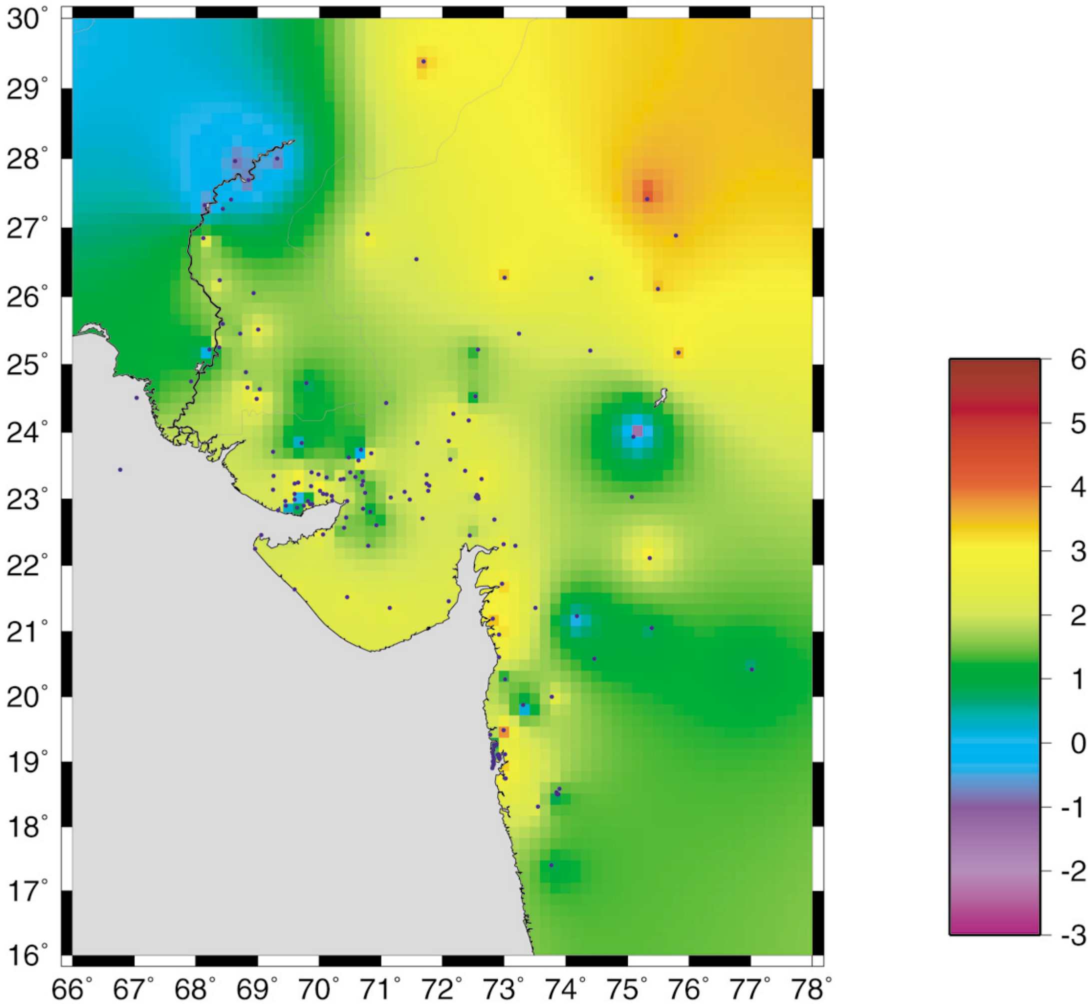


Figure 7. Residuals between our estimated MMI values for rock sites and those predicted by our preferred rupture model. For this figure, a different smoothing parameter (0.5) is used. This value is chosen because it produces a smoother interpolation between isolated points where the residuals are constrained. (A smoothing value of 1.0 produces sharp local maxima and minima.)

(The February mainshock was felt to greater distances, but Hough *et al.* interpret some "not felt" reports for this event as well.) These observations are inferred to imply only an upper intensity bound of III.

The comparisons are further complicated by uncertainties regarding the exact fault planes of the New Madrid earthquakes. The distances shown in Figure 9 are calculated not to presumed fault planes, as is done for the Bhuj observations, but to crude estimates of the earthquakes' epicenters. The high MMI values for both New Madrid earthquakes at 50–100 km may therefore reflect the difference distance measurements used.

From Figure 9, we conclude that it is difficult to distinguish the Bhuj intensities from those from either of the New Madrid events, perhaps suggesting that the December and February New Madrid events were of comparable size to the Bhuj earthquake. However, the question of sampling biases remains. It appears that sediment-induced amplification caused pockets of high ground motions at regional distances during both the Bhuj and New Madrid events. However, because the population of the United States' mid-continent was heavily concentrated along rivers in the early 1800s, the low-intensity shaking field was not well sampled in this case. Intensity values may therefore be systematically higher than those of later earthquakes, including Bhuj, for which the population distribution is more even.

A comparison between New Madrid and Bhuj intensities is also valid only if the two regions are characterized by similar propagation characteristics. Although the Indian shield region and cratonic central/eastern North America were both considered stable continental regions in the seminal work of Johnston (1996a), Bakun (pers. comm. 2001) has shown that the intensities are generally higher for large earthquakes in eastern North America compared with comparable earthquakes in India. Indeed, the $Q(f)$ values used in this study imply lower values between 1 and 7 Hz than

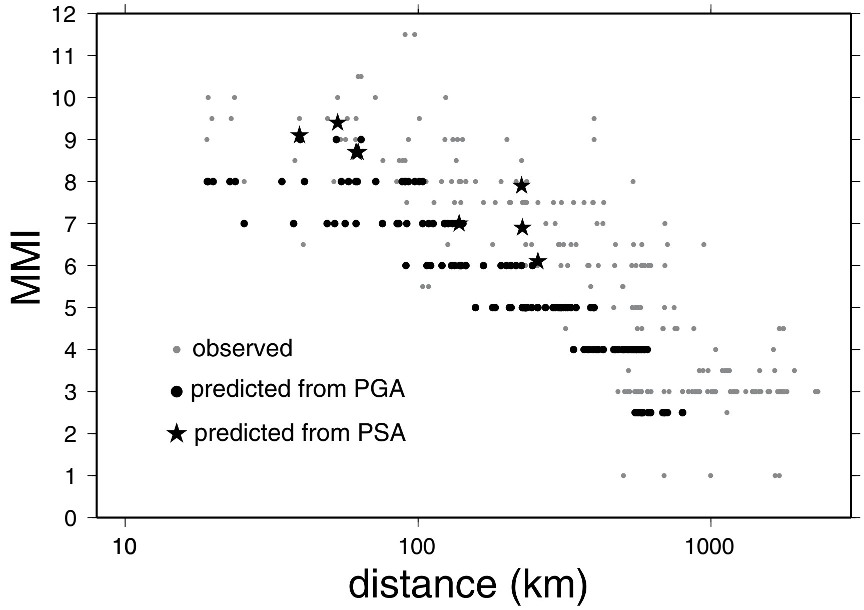


Figure 8. Our MMI values for the Bhuj earthquake are shown as a function of distance (small gray circles) along with predicted values calculated using an MMI–PGA relationship (large black circles) and one between MMI and response spectra (black stars).

$Q(f)$ determined by Benz *et al.* (1997) for both central and eastern North America (Fig. 10). Atkinson and Mereu (1992) also find higher $Q(f)$ values in southeastern Canada than those of Singh *et al.* (1999).

A relative calibration of MMI attenuation in India and North America is not yet available. We suggest, however, that the magnitude of the Bhuj earthquake, *M* 7.6–7.7, represents a credible upper bound for the two largest New Madrid mainshocks, although we consider it entirely possible, considering sampling bias and attenuation issues, that the New Madrid events were somewhat smaller. When a more thorough comparison of intensity attenuation in India and North America is available, it should be possible to draw a more quantitative conclusion regarding the magnitude of the New Madrid mainshocks.

Implications for the 1819 Allah Bund Earthquake

The 1819 Allah Bund earthquake in the northern Rann of Kachchh was discussed at length by Oldham (1926) in one of his last important contributions. His interest in this event was initially stimulated by his efforts to complete his father's account of Indian earthquakes (Oldham, 1883) and by the discovery of Baker's profile (Baker, 1846) during a clean-out of the Bombay office of the Geographical Journal of Bombay in 1896. Baker's profile across the Allah Bund had been accidentally omitted by the editor from his narrative describing surface deformation but forms the basis of a subsequent surface-rupture parameter estimation by Bilham (1998).

Oldham collated newspaper reports of the 1819 event to produce an isoseismal contour map. This map was used by Richter (1958) to produce one of the first magnitude estimates for the event. His magnitude, 8.0, was derived from a comparison of the felt areas of the 1819 event with those of the 1905, 1934, and 1950 Indian earthquakes for which he had derived surface-wave magnitudes. Recent recalibrations of these magnitudes suggest that many are inflated (Chen and Molnar, 1983; Ambraseys and Bilham, 2000).

Attempts to quantify the magnitude of the 1819 event from Oldham's isoseismal data were subsequently attempted by Johnston and Kanter (1992) and by Bilham (1998). Magnitude estimates varied from 7.6 to 7.9. A geological estimate of the magnitude has been proposed by Rajendran and Rajendran (2001), based on the estimated rupture length and a surface-slip estimate of 3 m. Bilham (1998) used Baker's profile to derive a geodetic moment magnitude of 7.7 $\pm$ 0.2.

The 2001 Bhuj earthquake stands to provide important new constraints on the magnitude of the 1819 event, in that the mechanisms and locations of the two events are very similar. In many cases, local construction practices have not changed. In some cases, the same historic structures were damaged by both events (e.g., the forts and town walls of Bhuj and Anjar). Yet there are important differences, in that some earthquake-resistant structures have been built in recent years; also, no concrete frame buildings existed in 1819.

A detailed intensity map for the 1819 earthquake is unavailable. However, Bilham (1998) does map sites that experienced severe and light damage, as well as sites at which the event was reportedly felt. We make crude MMI assign-

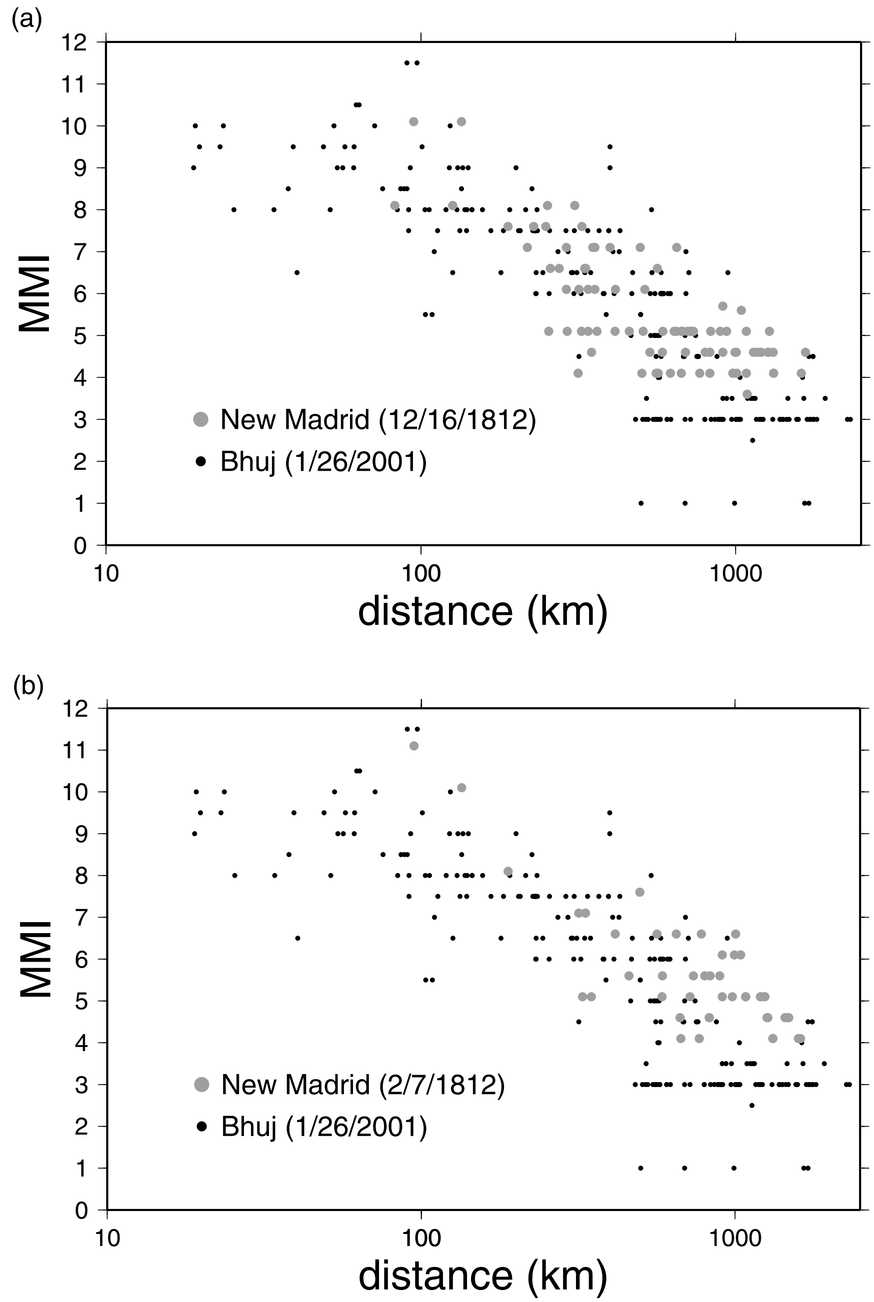


Figure 9. Our MMI values for the Bhuj earthquake are shown as a function of distance (small black circles) along with those determined by Hough *et al.* (2000) for the 16 December 1811 earthquake (large gray circles.) New Madrid MMI values are offset slightly upward for clarity.

ments of IX, VI, and III for these shaking levels, respectively (Fig. 11). A comparison of the isoseismal distribution of the 1819 and 2001 earthquakes shows that they are virtually indistinguishable in overall characteristics. Both events were felt lightly on the eastern coast of India; both caused light damage to distances of 500–600 km; and both caused heavy damage to distances of approximately 100 km (Fig. 11). (The extent of the high-intensity region is larger for the 1819 earthquake than it is for the Bhuj earthquake, but we attribute this to the sparsity of the 1819 data and our inability to assess precise MMI values for each site where "severe" damage occurred.)

We therefore conclude that the magnitude of the 1819 Allah Bund earthquake was also likely to have been very close to 7.6. This value is within the uncertainties of previous estimates but suggests that rupture dimensions and/or slip in 1819 may have been somewhat smaller than the values permitted by the higher geological and geodetic estimates.

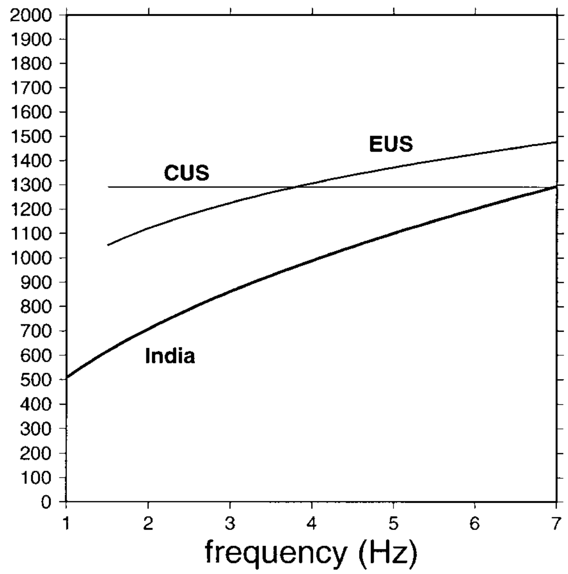
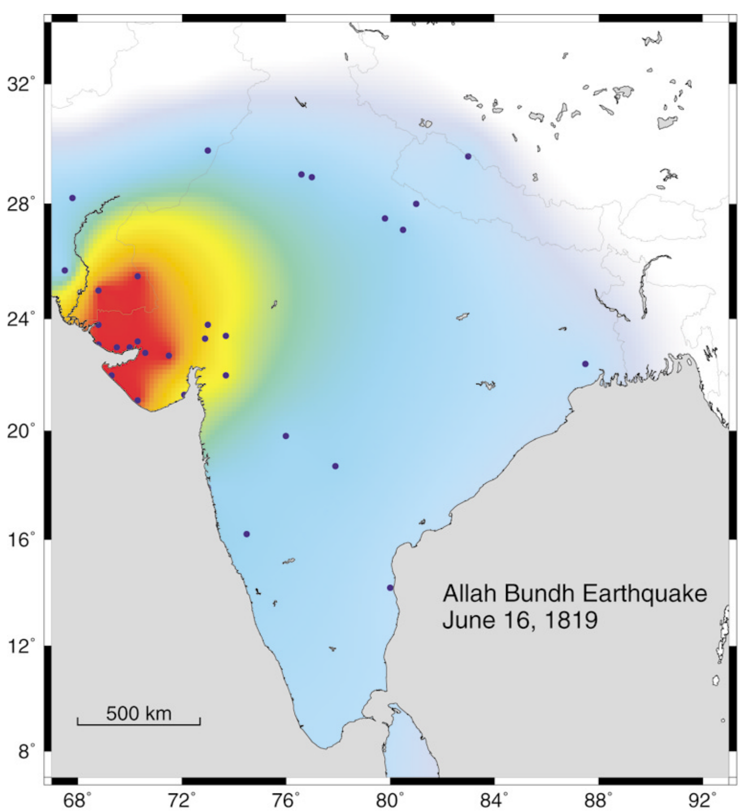


Figure 10. Attenuation function used in this study (Singh *et al.*, 1999) is shown (dark line) along with $Q(f)$ inferred for the central United States (CUS) and eastern United States (EUS) by Benz *et al.* (1997).

Discussion and Conclusions

We have compiled media-based intensity maps for the 26 January 2001, Bhuj earthquake. These maps, based only on news accounts of the event, allow us to map the general distribution of shaking effects; they will also ultimately provide insight into the potential biases associated with determination of intensities based solely on media accounts. Such results are expected to be very useful, as the 2001 Bhuj earthquake has important implications for earthquake hazard, not only in India but also in other parts of the world where the source zones and/or the wave travel paths are similar (although the degree of similarity clearly bears further investigation). On the basis of our results and the similarity between their intensity distributions, we conclude that the 1819 Allah Bund earthquake had a magnitude very close to that of the 2001 Bhuj event: 7.6 ± 0.1. Our results also suggest that the magnitudes of the two largest 1811–1812 New Madrid earthquakes were slightly smaller than that of the Bhuj event, although the difference is difficult to quantify.

Our results show that, especially in the absence of modern instrumentation, MMI data can provide important information about the distribution of ground motions. As dis-



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 11. Distribution of shaking effects from the 1819 Allah Bund earthquake, from Bilham (1999), compared with those determined in this study for the 2001 Bhuj earthquake.

cussed earlier, site-response patterns are quite evident in the intensity distribution at both near and far distances. The overall felt distribution of the event also provides insights into the nature of *Lg*-wave propagation. Hanks and Johnston (1992) showed that the far-reaching effects of central/eastern United States earthquakes can be explained by the efficient propagation of *Lg* waves (i.e., higher-mode surface waves) within cratonic North America. Kennett (1989) showed that *Lg* waves will propagate efficiently within a waveguide but will be disrupted when they encounter complexity such as crustal thickening. The felt area of the Bhuj earthquake is contained almost entirely within the Indian subcontinent. Our results therefore provide observational confirmation of the modeling results of Kennett (1989), that *Lg* waves are significantly disrupted by large-scale crustal complexity.

Our finite-fault-modeling results show that our estimated MMI values provide a good indication of the distribution of ground motions (PGA). Although the predicted hard-rock shaking level is lower than that inferred from macroseismic observations, we conclude that site response can explain most of the discrepancy. We have discussed three additional possible factors that might also contribute to the discrepancy: (1) extreme vulnerability of buildings in the Kachchh region, (2) a tendency of news accounts to focus on the most dramatic damage, and (3) the nature of the ground motions in intraplate crust. Although the first factor has been widely discussed, it is unlikely to account for the discrepancy in regions that experienced moderate (MMI IV–VI shaking). We also note that the discrepancy is no larger in the epicentral region than at regional distances, which perhaps suggests that building vulnerability was not an important factor at close distances. This would not be an altogether surprising result, as building type and vulnerability are taken into account when MMI values are assigned.

At present, it is difficult to assess the effect of a possible media bias, although we consider to likely that such a bias did contribute to the discrepancy. A comparison with a survey-based intensity map will ultimately allow us to constrain the magnitude of this effect. This result will have implications for the interpretation of historical earthquakes for which the only available information is from printed media sources.

The final possibility, that the Bhuj ground motions were unusually damaging because of their high high-frequency energy, is interesting to consider. To compare predicted and estimate MMI values, we have used a relationship between MMI and PGA determined from recent large earthquakes in California. However, it has been suggested that large intraplate earthquakes might be more damaging than their interplate counterparts for reasons discussed earlier (e.g., Greig and Atkinson, 1993; Atkinson, 2001). We therefore also compared predicted and estimated MMI values by using a relationship between MMI and response spectral amplitudes (Atkinson and Sonley, 2000). Although also developed for California earthquakes, Atkinson (2001) concludes that the relationship is appropriate for earthquakes in eastern North America, at least for distances of 150 km or less. Our results show that, using the response spectral regressions, our predicted ground motions imply rock MMI values approximately 1 unit higher than those estimated from the MMI–PGA relationship. For soil sites, the predicted MMI values would be about 1 unit higher than for rock sites. Thus, there would be no significant discrepancy between observed and predicted MMI values.

Although much work remains to be done, the Bhuj earthquake provides important information to better understand the hazard posed by earthquakes that occur in and/or affect intercratonic regions. In addition to insights into the nature of source zones in low-strain-rate environments, the event provides invaluable new information with which ground motions from the past and future large intracratonic earthquakes can be better understood. The analysis presented here highlights the critical need to develop and test relationships between MMI and both PGA and response spectral ordinates for intraplate regions, and also to investigate in detail the attenuation of intensity in different intraplate regions.

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